PART IV = Soil with Water - No Flow or Steady Flow

(i.e., u in soil controlled by u at boundaries)

IV-1 EFFECTIVE STRESS PRINCIPLE AND CAPILLARITY

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1. Effective Stress Concept

2. Capillarity

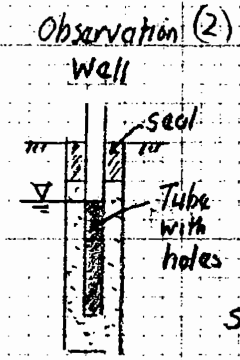
Part IV-1 EFFECTIVE STRESS PRINCIPLE & CAPILLARITY

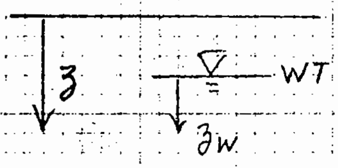
1 EFFECTIVE STRESS CONCEPT

1.1 Definition & Misc

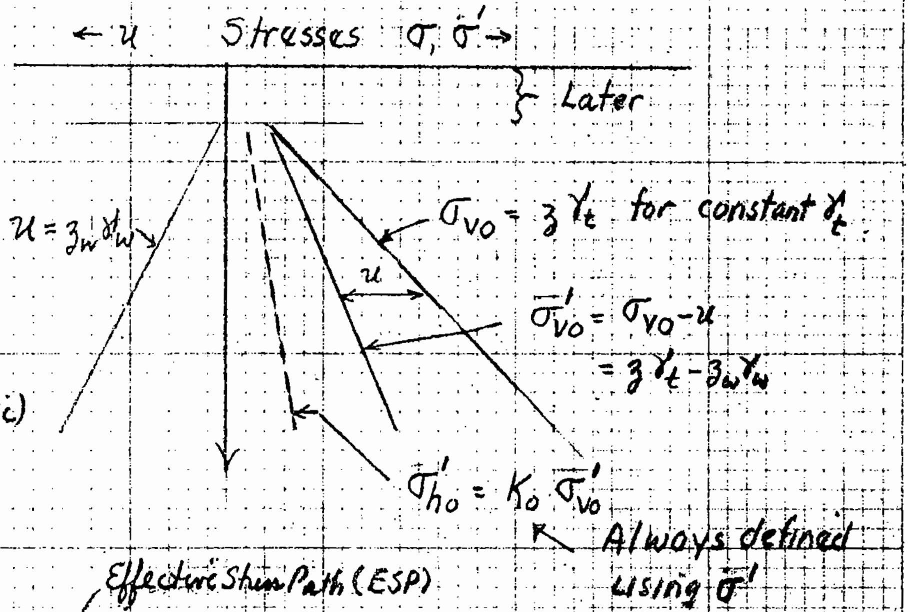
(1) Principle
- $\bar{\sigma} \equiv \sigma' = \sigma - u$ (equivalent of f=ma in mechanics)
- (S=100%) σ' "controls" stress-strain-strength behavior

(2) Geostatic conditions (+ hydrostatic pore water pressure, u)



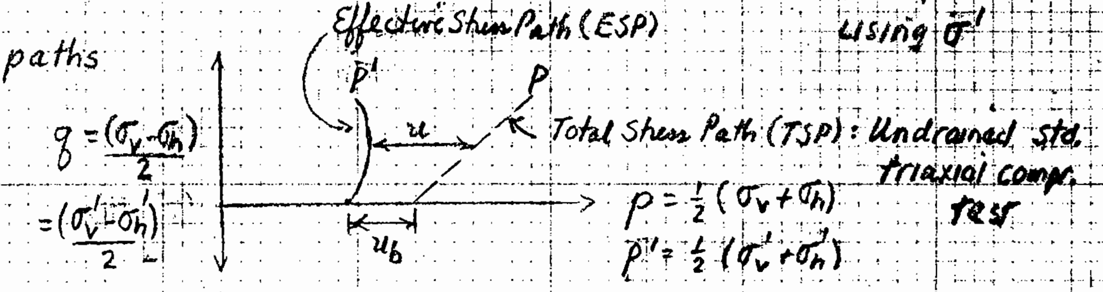


Soil with constant e



- Water table = location where u = 0 (atmospheric) = phreatic surface
- How measure?

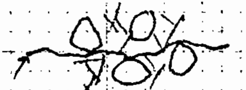
(3) Stress paths



1.2 Physico-Chemical σ' Eqn. (S=100%)

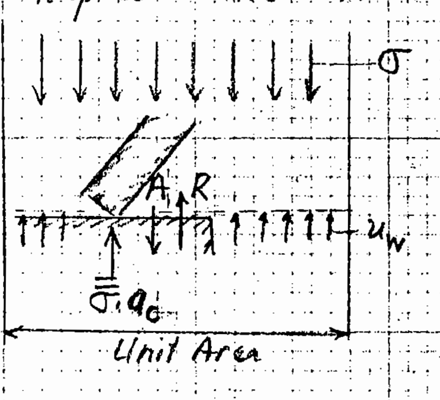
(1) Model (From Section 2.5, Part II-2)

Saturated Soil



"Wavy" line thru contacts

Representative Unit Area



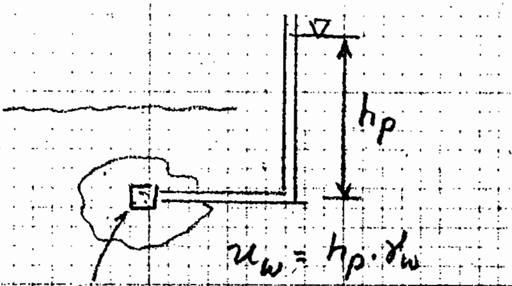
- $\sigma = \underbrace{\bar{\bar{\sigma}} \cdot a_c}_{\text{Net contact}} + \underbrace{(R-A)}_{\text{Net D.L.}} + u_w \cdot a_w$

pore water pressure

area over which u_w acts

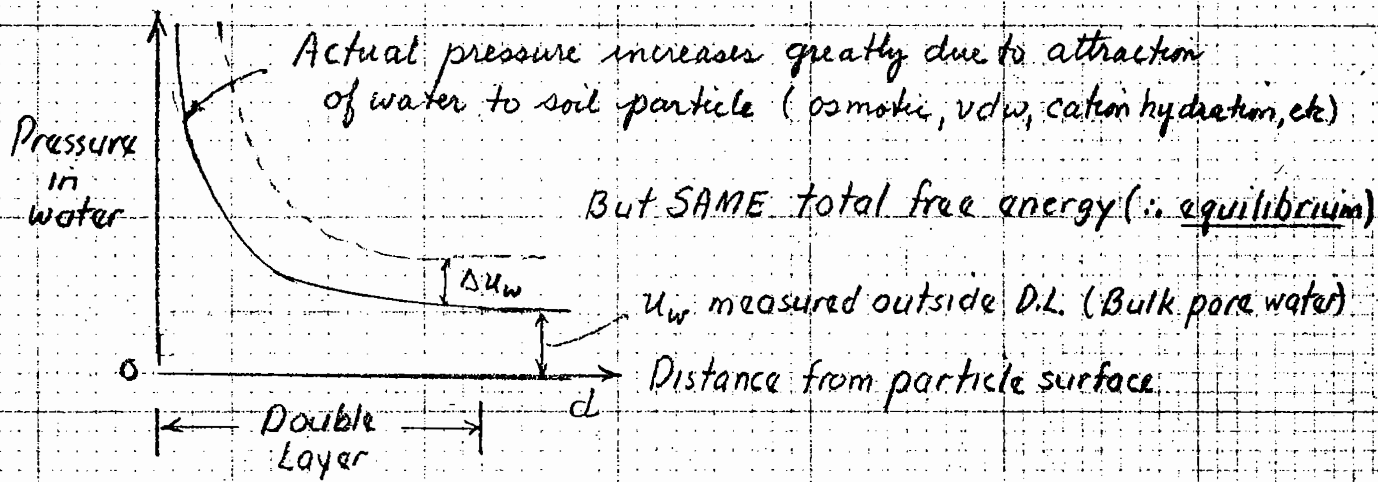
(2) Definition of u_w = <u>Measured Quanity</u>

- u_w = pressure that must apply to water in contact with soil element to prevent water from flowing in or out of the soil
- u_w is measured via PIEZOMETERS



Porous tip of <u>piezometer</u>
(with same pore fluid as bulk water in soil)

(3) Physical significance vis-a-vis <u>actual</u> u_w



Actual pressure increases greatly due to attraction of water to soil particle (osmotic, vdw, cation hydration, etc)

But SAME total free energy (∴ <u>equilibrium</u>)

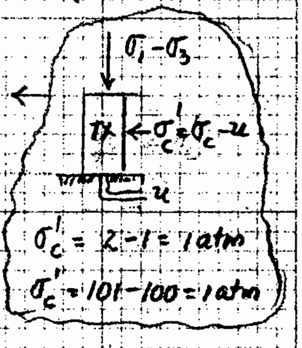
u_w measured outside D.L. (Bulk pore water)

Distance from particle surface

- If increased u_w by Δu_w, then get increase everywhere excepts
  (1) No water (2) "Structure" of water can resist shear stresses ("ice like")

Hence a_w reflects area where Δu_w acts

BUT experimental evidence shows that $a_w \approx 1.00$ ←
for soils (not true for rock). Important finding for offshore clays where $u_w \to$ 100s atm.



(4) <u>Review of Section 2.6, Part II-2</u>

- $\sigma' = \sigma - u = \bar{\bar{\sigma}} \cdot a_c$ ← generates shear resistance
  $+ (R - A)$ ← influences Δu & $\Delta Vol.$

i.e. σ' transmitted thru soil skeleton via contact & DL stresses

- Granular soils

$$\underset{\substack{\uparrow \\ \text{10,000's atm}}}{\sigma' = \bar{\bar{\sigma}} \cdot a_c}$$

- Cohesive Soils

$$\sigma' = \underbrace{\bar{\bar{\sigma}} \cdot a_c}_{} + (R - A)$$

← Usually > 90% at low OCR

← Exception: dispersed Na mont.

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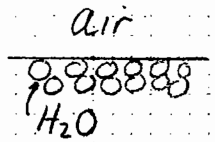
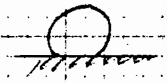
Part IV-1 ESP & CAPILLARITY

2. CAPILLARITY (For stresses in soil above WT having $S \leq 100\%$)

2.1 Surface Tension (T_s)

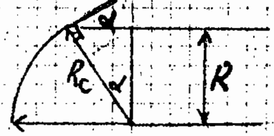


- H_2O molecules attract each other so that water surface wants to → minimum area
- Surface Tension, $T_s = \frac{\text{energy}}{\text{unit area}} = \frac{J(=N\cdot m)}{m^2} = \frac{N}{m}$

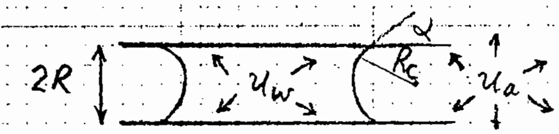


$T_s = 0.073\ N/m = 0.074\ g(ft)/cm$ for air-water interface at room temp.

T (°C) =	0	10	15	20	25	30
T_s (N/m) =	75.7	74.2	73.5	72.75	72.0	71.2 $\times 10^{-3}$



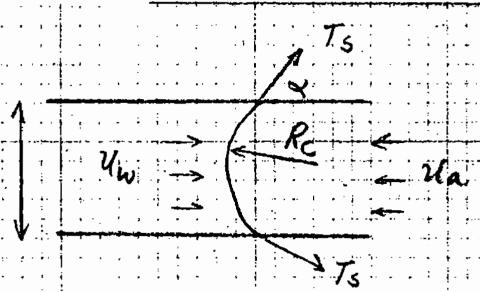
2.2 Capillary Pressure, u_c



Glass Capillary Tube

R_c = radius of curvature
$= R/\cos\alpha$

Σ Forces ∥ to Tube



$$(u_a - u_w)\pi \underbrace{R_c^2 \cos^2\alpha}_{R^2} = T_s \cos\alpha \; 2\pi R$$

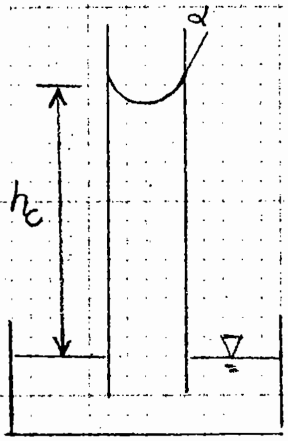
$$(u_a - u_w) = \frac{2T_s\cos\alpha}{R} = \frac{2T_s}{R_c = \frac{R}{\cos\alpha}}$$

By necessity:
- $u_w < u_a$
- u_w negative for $u_a = 0$

u_c = capillary pressure $\equiv (u_a - u_w)$

Also called soil suction(s), especially with cohesive soils (See Section 2.6)

2.3 Capillary Rise in Tube



Isolate water column, $\Sigma F_v = 0$

$$\gamma_w h_c \pi R^2 = T_s 2\pi R\cos\alpha$$

∴ h_c = max. height of capillary rise

$$= \frac{2T_s}{R\gamma_w}\cos\alpha = \frac{2T_s}{R_c\gamma_w}$$

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Part IV-1 ESP & CAPILLARITY

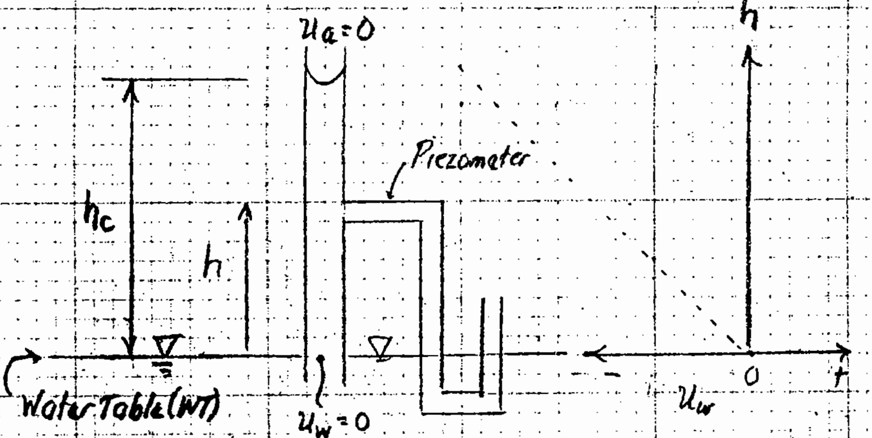
p4

2.3 (Continued)

(1) For soil & clean glass, $\alpha \to 0$

$$\left\{ h_c(\text{cm}) = \frac{2T_s}{R \cdot \underbrace{\gamma_w}_{1\,g/cc}} \doteq \frac{0.15}{R(\text{cm})} \right.$$

Soil	R	h_c
Fine sand	0.1mm	15cm
Clay	$1\mu = 0.001$mm	15m



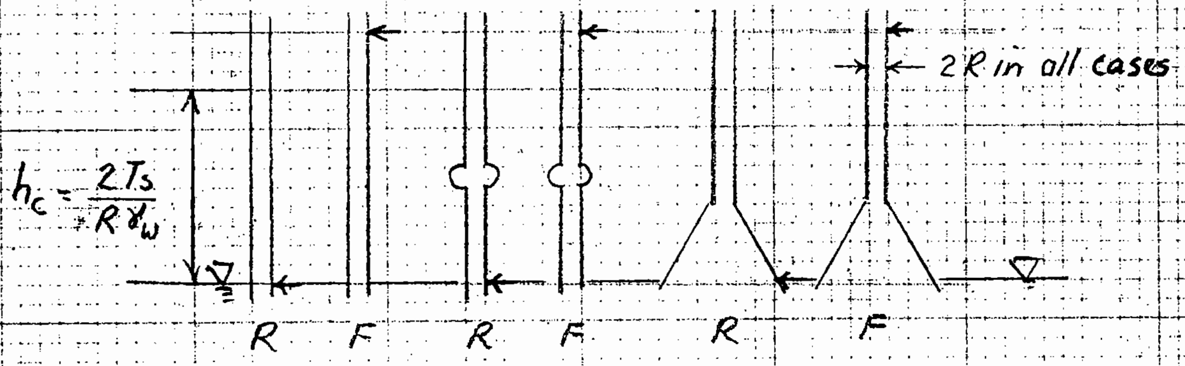
- u_w vs. $h \to u_w =$ ______
- At $h = h_c$

$$h_c \gamma_w = \frac{2T_s}{R} = (u_a - u_w) = u_c$$

$\therefore u_w =$ ______ for $u_a = 0$

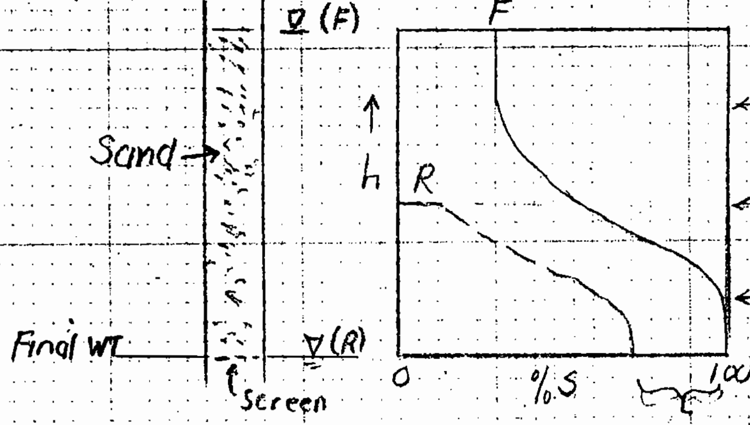
- Can u_w be less than -1 atm? YES (à la Section 2.6)

2.4 Examples - Capillary <u>R</u>ise & <u>F</u>all (← Initial height of water)



$$h_c = \frac{2T_s}{R\gamma_w}$$

2.5 Soil Capillarity (Fig. 16.4)



} Discontinuous H_2O $u_w \neq -h\gamma_w$

h_{cx} = max. cap. head ($u_w = -h\gamma_w$ since continuous water)

h_{cr} = capillary <u>rise</u>

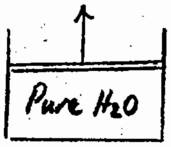
h_{cs} = saturation h_c

Due to entrapped air

2.6 Soil Suction in Cohesive Soils

1) Tensile strength of water [Ridley & Burland, 1993: Geot. 43(2)]

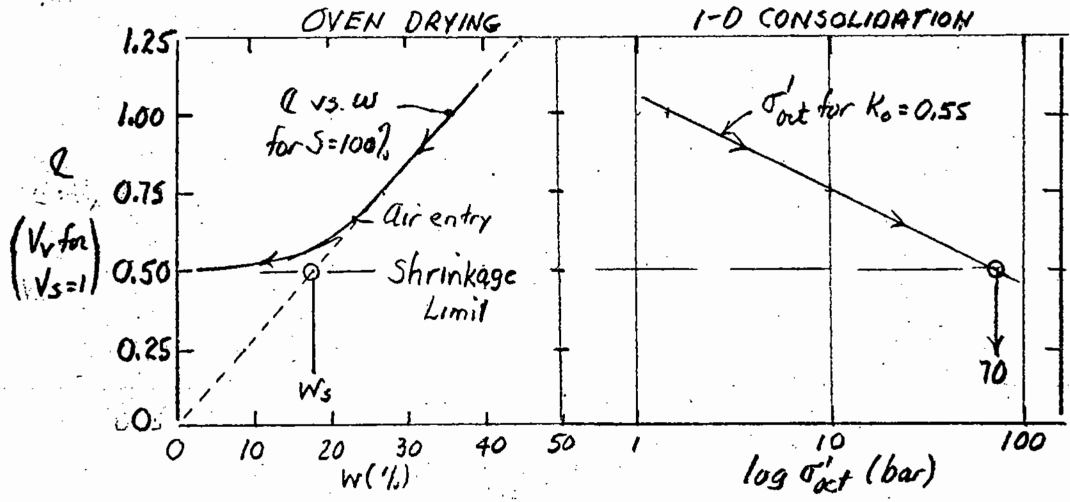
- Tabor (1979): theoretical value of $u_w \approx -5000$ bar!
- However, very small amount of dissolved gas in measurement system → cavitation at $u_w \gg$ theoretical value, i.e., typical field piezometers & lab tensiometers will cavitate at $u_w \approx -0.8$ bar



- With carefully degassed, smooth walled chamber, have measured $u_w \approx -500$ bar [Temperley & Chambers 1946: Proc. Royal Soc., London]

2) Can cohesive soils develop large negative values of u_w?

- Look at drying vs 1-D consolidation of Resedimented BBC ($I_p = 25\%$)



- Conclusion: cohesive soils can develop negative u_w → tens-hundreds atm.

3) Components of soil suction, $s = u_a - u_w$ [Aitchison & Richards, 1965 Sym. in Australia: Butterworth]

- Total suction (s_t) = Matric suction (s_m) that causes σ' to act on soil skeleton
  + Solute suction (s_s) due to osmotic pressure of dissolved salts in bulk pore water of soil
- Total suction is a measure of the free energy of the bulk water in the soil compared to pure H_2O at atmospheric pressure (at same temp. & elevation).

3) <u>Continued</u>

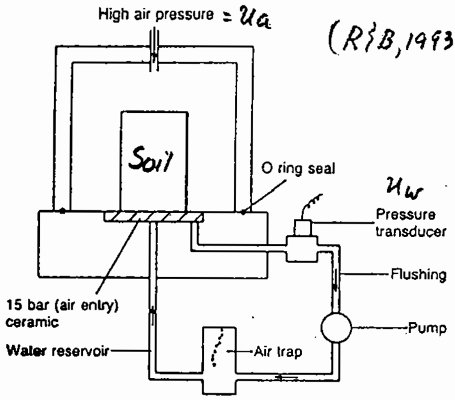
Solute suction S_s (bar) = 24.4 [total salt conc. = $\Sigma(C_a + C_c)$ in moles/liter = M]
(from Section 2.3, Part II-2), at $T = 20°C$) $\Rightarrow$ S_s (bar) = 24.4 $(2C_0)$ for $C_0 = C_a = C_c$

Examples: Conc.(M) =	10^{-3} NaCl	0.1 NaCl	Sea water 35g/l ≈ 1.1M ($C_a + C_c$)
S_s (bar =	0.05	4.9	27

4) <u>Laboratory measurements of soil suction</u> (Fredlund & Rahardjo 1993: <u>Soil Mech for Unsaturated Soils</u>, John Wiley)

a) <u>Direct</u>: Tensiometer = miniature piezometer with a fine porous stone (BP = bubbling pressure must be ≥ measured S_m)
Ridley & Burland (1993) & Kurt Sjoblom (MIT PhD, 9/00) have developed devices to measure $S_m \to$ 15 bar in few minutes. Key features = 15 bar stone, very small water reservoir, v. stiff transducer & 10 bar saturation pressure

b) <u>Semi-Direct</u>: Pressure Plate (and similar variations)



(R&B, 1993)

(1) Increase u_a to get u_w above −1 atm to prevent cavitation within system

(2) $S_m = u_c = (u_a - u_w)$. However, uncertain interpretation unless have either S = 100% or continuous air voids

(3) Need to remove specimen after each "test" to measure w. Hence takes days to obtain Soil Moisture Characteristic curve = S_m vs w

c) <u>Indirect</u>

Section 2.1, Part II-2

(1) Measure w at varying relative humidity. Total $S_T = 1350 \ln(100/RH)$ @ 20°C
Takes weeks/measurement & restricted to $S_T \geq 10$ bar (RH ≈ 99%)

(2) Filter paper (FP). Need calibrate w of FP as f (RH) via different salt solutions & use above eqn. to get S = f(RH).
• FP in contact with soil $\to S_m$
• FP not in " " " $\to S_T$
} Takes 1-2 weeks/measurement. Not accurate $S \leq 1$ bar

(3) Thermal conductivity (TC) measured for ceramic sensor in contact with soil.
Need calibration of TC = f (w of ceramic) = f (applied suction).
Takes ≈ 1 week/measurement.

5) <u>Field measurements of soil suction</u>

See Stannard [1992, ASTM, GTJ, 15(1)]

6) <u>Some values of matric suction for soils compacted at optimum water content for "Standard" Compaction effort</u>

⬡ Olson & Langfelder [1965, ASCE, JSMFD, 91(4)]

○ Krahn & Fredlund [1972, J. Soil Science, 114(5)]